Validation of the surge model and lessons learnt from commissioning of the Shuweihat Water Transmission Scheme, UAE

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Abstract

This paper presents a validation of the surge modeling results as well as lessons learnt from the commissioning test of the Shuweihat Water Transmission Scheme in the UAE. The Scheme is divided in two systems, The first system (Lot A) transmits water from Shuweihat to Mirfa (100 km). The second (Lot C) is from Mirfa to Mussafah (150 km). The focus of this paper is on the model predictions and field data recorded by the SCADA system during full pump trip and valve closure events. The validation was performed during the commissioning test and showed a perfect match between the prediction and measurement of pressure and flow of the first wave. This paper also intends to highlight lessons learnt during the commissioning test and in particular the major risk that is caused by inaccurate manufacturer data. On the first day of the commissioning test, a near incident took place where the pressure during valve closure unexpectedly exceeded the pressure rating by 16%. Damage to the pipeline was avoided by pressing the emergency trip push-button of the pumps thereby preventing the pipeline from being exposed to the full pressure rise. The post-incident investigation revealed that the control valve characteristics provided and certified by the manufacturer were inaccurate. A difference in Kv of up to 20% was measured for valve positions below 40% open and the valves were fully closed at 5% opening. The control valve characteristics were recalibrated on site and the valve closure pattern was adapted. The commissioning test was resumed and completed flawlessly.

Introduction

The Shuweihat Water Transmission Scheme (SWTS), United Arab Emirates, consists of two ND1600 Ductile Iron pipelines transporting distillated water from the Shuweihat desalination plant to Mussafah (Abu Dhabi area), via the Mirfa tank farm and its desalination plant. The purpose of the pipeline is to transport the entire Shuweihat distillate production of 150 MIGD (28,410 m^3/h) to the major population centers in the UAE as well as remote desert dwellings along the coastline.

The Transmission and Despatch Company of Abu Dhabi (TRANSCO) owns and operates the pipeline system. The main contractor is Marubeni Taisei Consortium (MTC) and the consultant of the owner is Tebodin Middle East (TME). Deltares (formally known as WL | Delft Hydraulics) was commissioned by MTC to perform the hydraulic study of the scheme.

This paper focuses on the modeling and commissioning test of a segment of the scheme from Shuweihat to Mirfa (100 km length). The most severe surge scenarios (full pump trip and emergency shut down) were performed at a variety of flow rates, from low flow rates up to the maximum design flow rate. The results for these cases, as obtained from the SCADA system are presented and then compared with the prediction of the surge model. Finally, this paper also intends to highlight lessons learnt during the commissioning test and in particular the major risk that is caused by inaccurate manufacturer data.

Surge protection approach and Acceptance criteria

Two sets of acceptance criteria have been used for the project depending on the availability of the SCADA system and the Fiber Optic Cable (FOC).

In the case of a healthy control system, stringent acceptance criteria have been used. These are the maximum pressure of 25 barg and the minimum pressure above atmospheric pressure (0 barg). In order to achieve such criteria, the surge protection approach relies on the coordinated action of the pumps and the downstream control valves. In case of full pump trip, the control stations close in a certain way to prevent negative pressures. In this case, the air vessels are providing a sufficient damping as to allow for smooth pressure variations. On the other hand, in the case the receiving stations are closed (simultaneously), the pump station will trip in a timely manner in order to limit the maximum pressure surge. In all cases, the restart after trip was to be made against a fully pressurized pipeline thereby resuming normal operation in the shortest possible time.

In the case of an unhealthy control system or fiber optic cable, the client did not wish to reduce the maximum capacity of the pipeline. Yet, safe operation was to be maintained even if communication between the various stations (pump station, distribution receiving station and terminal receiving station) was interrupted. In such case, the acceptance criteria were somewhat relaxed with the maximum pressure to be maintained below 30 barg and the minimum pressure above -0.5 barg. The approach was to safeguard the pipeline from any damages while allowing some air pockets to enter the pipeline. The restart procedure is in such case longer than with a healthy control system as the air pockets need first to be vented.

Software

WANDA 3.71 was used to perform the simulations. This software has been developed by Deltares (formerly WL | Delft Hydraulics) in the Netherlands. WANDA is an interactive software package for hydraulic analyses of pipeline systems. WANDA includes three modules, Engineering, Transient and Control, to support the entire life cycle of a pipeline system: basic design, detailed design, commissioning, operation, maintenance procedures and temporary and permanent modifications.

WANDA is the successor of WILMA, which has been developed and applied since the 1970s. Many individual component models of WANDA have been validated against laboratory and field data. A subset of representative scenarios has been collected in a validation report (Pothof, 2006), which has been updated on a regular basis (Zwan, 2008; Tukker 2012).

Description of the system

The profile of the pipeline is in general flat, with both ends of the pipe at similar elevations (4 m). There are a few local high point at 38 km, 62 km and 82 km. Air valves are installed at this location and greatly influence the surge behaviour of the pipelines.

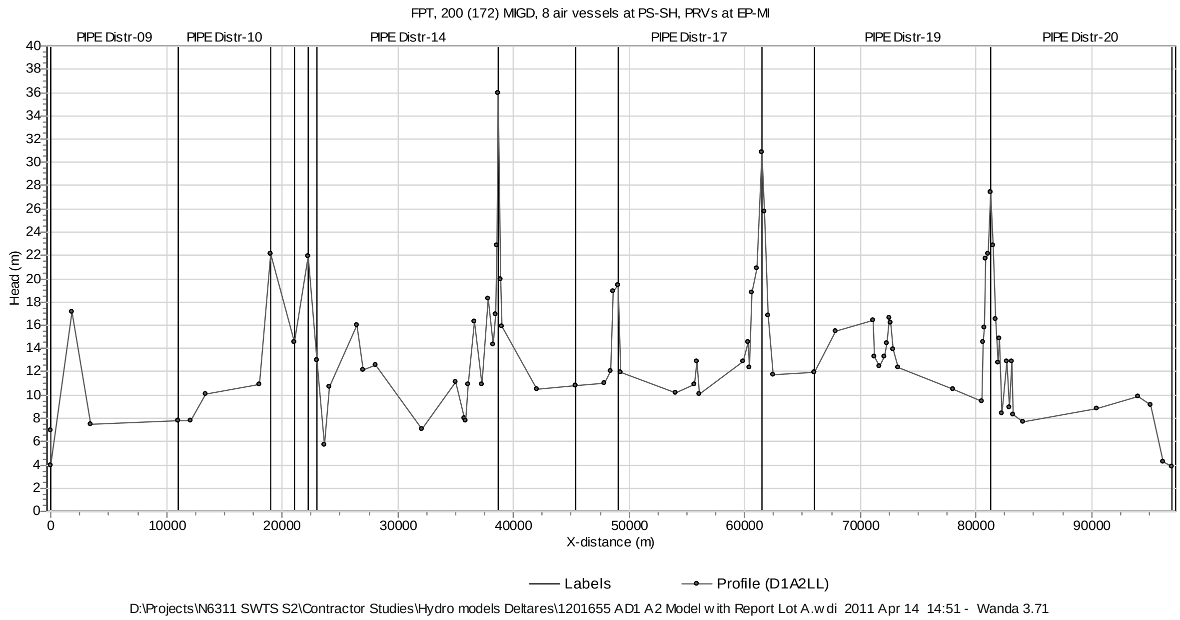

Figure 1 Shuweihat to Mirfa, Pipeline profile

Six pumps in total are installed in Shuweihat pump hall. The maximum flow rate (14,205 m^3/h) is reached by operating 3 pumps at the rated flow of 4,735 m^3/h. Normal operation is two pumps in operation at maximum pump flow (5,682 m^3/h) for a total pipeline flow of 11,365 m^3/h.

Vertical non-vented air vessels have been installed at the pumping station. Five vessels of 121.4 m^3 are installed on each line (607 m^3). The vessels are controlled by the fluid level which needs to be maintained between the High High Water Level and the Low Low Water Level by a compressor and solenoid valve. The distance between HHWL and LLWL is 1 meter.

Single orifice twin DN250 air valves are installed at every local high points and in average every 800 m. Air valve parameters are modelled based on matching the characteristic curve.

Based on manufacturer data, the control valves installed at the receiving point of Mirfa (DN800), Mussafah (DN800) and Unit IV (DN900) had the following hydraulic characteristics.

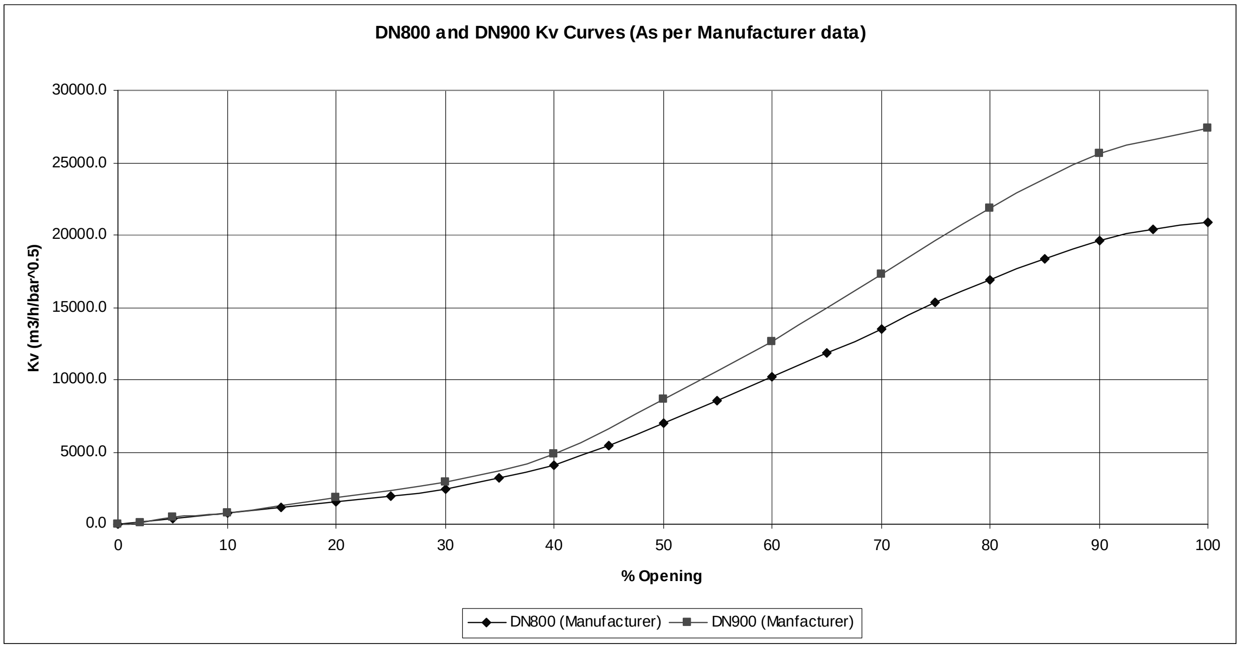

Figure 2 Kv of the control valve as per manufacturer data

The cavitation number of the valve was not provided by the manufacturer. The data above was used for the simulation of emergency shut down scenario and thus the design of the closure pattern as shown here below. In addition, in case no FOC was available, the initial closure of the valves was designed to trigger the local tripping of the pump station based on a deviation of flow and pressure (see control system below).

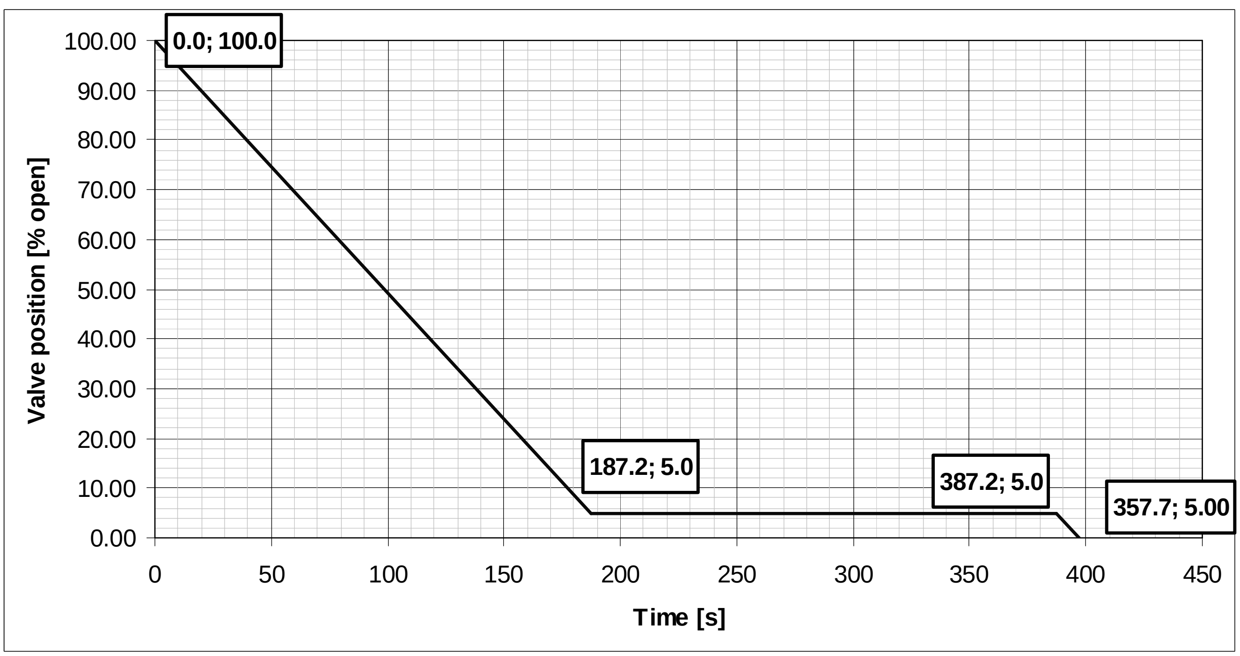

Figure 3 Closure pattern (pre-commissioning) of Lot C tank inlet valves

Given that these safety features were critically depending on the accurate knowledge of the Kv characteristics of the control valve and the fair certainty that cavitation resulting in smaller flow rates would not occur at critical times during the closure pattern. The manufacturer confirmed that the closure patterns involving position up to 5% opening were suitable for the control valve.

Safety controls are present in the system and the model. These are based on hydraulic data recorded locally at Shuweihat. The safety control monitors the variation of flow and pressure at Shuweihat and compares these values to the normal operation system curve of Lot A. It is required in order to protect the system against the effects of an emergency shut down. This control is in operation at any time and for any flow rate.

The control has two loops (see **Error! Reference source not found.**):

1. When either of the pressure or the flow deviates from the steady state functioning point by 25% for 10 continuous seconds, the pumps are tripped.
2. When either of the pressure or the flow deviates from the steady state functioning point by 35% the pumps are tripped instantly.

Table 1 Safety setting for P4000. Pressure and flow variation triggering a FPT

Factor of Deviation of Pressure increase	Factor of deviation of Flow rate decrease	Signal Remains true duration
+25%	-25%	10 s
+35%	-35%	0 s

Extreme Cases Description

The following two extreme case scenarios are tested during the trial operation:

- ESD (Emergency Shut Down):

This scenario consists of the simultaneous closure of all downstream valves resulting in a rapid increase of the pressure in the pipeline, which triggers the safety controls.

- FPT (Full Pump Trip):

This scenario consists of the simultaneous trip of all active pumps. It causes a decrease of the pipeline pressure which is attenuated by the air vessels. The downstream valves stay in automatic mode and therefore close when the pressure decreases.

Table 2 Schedule of scenarios investigated during the commissioning tests

Test number	description	Surge action	Date	Time
T0	Transmission line at 60MIGD	ESD	21-08	
T1	Transmission line at 60MIGD	ESD	22-08	13:00
T2	Transmission line at 60MIGD	ESD	22-08	15:15
T3	Distribution line at 60MIGD (branches closed)	ESD	22-08	17:20
T4	Transmission line at 60MIGD	FPT	22-08	18:45
T5	Transmission line at 75MIGD	ESD	23-08	14:15
T6	Transmission line at 75MIGD	FPT	29-08	13:45
T7	Distribution line at 75 MIGD (branches closed)	ESD	29-08	21:00

Commissioning test results

The trial operation of S1 was held between August 21st and August 29th 2007. The objective of the test was to validate the results obtained through the extensive surge modelling and to make sure that all the safety features of the pipeline were working properly. It was proposed to conduct the commissioning test in several phases, starting by determining the actual roughness of the pipeline and then proceed with Full Pump Trip and Emergency Shut Downs at increasing flow rate. The final test was to be conducted at the maximum flow rate of 75 MIGD per pipeline.

For each of these tests, data were collected from S1 (Shuweihat) and Mirfa control rooms. The hydraulic model built in Wanda was used prior to the test and after the test and the results were compared. Before the commencement of the test, the initial steady state condition was modeled and the surge action was simulated with Wanda. After the completion of the test, the hydraulic model was calibrated in order to match the observed results.

Roughness Calculation

The roughness of the pipeline was measured based on data output from the SCADA system. The input used was the pressure at the pump station and the various receiving stations. All Pressures were converted to head based on as built drawings. The data was included in the hydraulic model and the roughness was determined through a basic iteration process. Initially, simulations were performed at the roughness of 0.10 mm (new pipe, as advertised by manufacturer) up to 0.50 mm (old pipe). The internal diameter of the pipeline is 1,612 mm.

The roughness was calculated to be 0.15 mm for Lot A (0.13 mm for Lot C). At the time of calibration, the pipeline had been under limited operation for approximately 2 years with flushing and operation at reduced flow rates (maximum 40 MIGD). The roughness was higher than the one advertised by the manufacturer (0.10 mm), leading to 6% more friction loss at the design flow rate.

Initial Test T0 (initial trial test)

The execution of trial test T0 consisted of increasing the pipeline flow rate from 40 MIGD to a steady flow rate of 60 MIGD. Once this flow rate is achieved, the valves at the end of the pipeline were closed instantaneously through operation of the Shuweihat Control system. The closure pattern as designed in the surge study had been programmed in the DCS and was closely monitored in the control room.

The purpose of the test was to verify the correct implementation of the control valve closure pattern as well as the effectiveness of the pumps safety mechanisms designed to trip the pumps based on local flow and pressure deviations.

The test was initiated and the closure of the valve proceeded as planned and the recorded pressure at the upstream side of the control valve followed closely the prediction of the surge software. However, as the control valve position approached the freeze position (5% opening), the recorded pressure continue to increase and exceeded significantly the predictions. To safeguard the pipeline, the decision was made within one minute to manually trip the pump and to end the test.

Post test simulation with the surge software showed that the pressure recorded on the DCS was consistent with a direct closure of the control valve, without freeze period. Yet, the DCS clearly showed that the valves were stopping their travel at the correct opening and maintaining that position for the correct duration. It was concluded that the Kv characteristics of the valves were not correct and were either different from the manufacturer data or affected by cavitation.

Establishing the real Kv characteristics

Deltares proposed to the contractor and the owner to proceed with an in-situ verification of the Kv Characteristics of the control valves. It was stressed that such verification could be of limited accuracy since only site equipment of limited accuracy was available.

The test objective were to determine the Kv properties of each control valve from a position of 40% opening down to 5% opening in small steps (from 5% to 2% steps). During the test, the valve was moved in manual model to the desired position and sufficient time was given to allow for the stabilization of the flow. After stabilization, the upstream pressure and flow were recorded. The downstream pressure was approximated based on the elevation of the tank. A number of measurement errors were unavoidable due to equipment or lack of equipment but the final results were deemed fit for purpose.

The characteristics of the valve were measured once in the opening sequence (from 40% down to 0%) and again on the opening travel (from 0% to 40%) in order to check firstly whether there was a shift in valve position between closing and opening (through visual inspection) and also to compare the Kv in both travel direction. This test showed that no position shift occurred between opening and closure.

Finally, an operator was stationed next to the measured valve in order to report any sound of cavitation and eliminate cavitation as a possible cause for the Kv variation. No cavitation was reported.

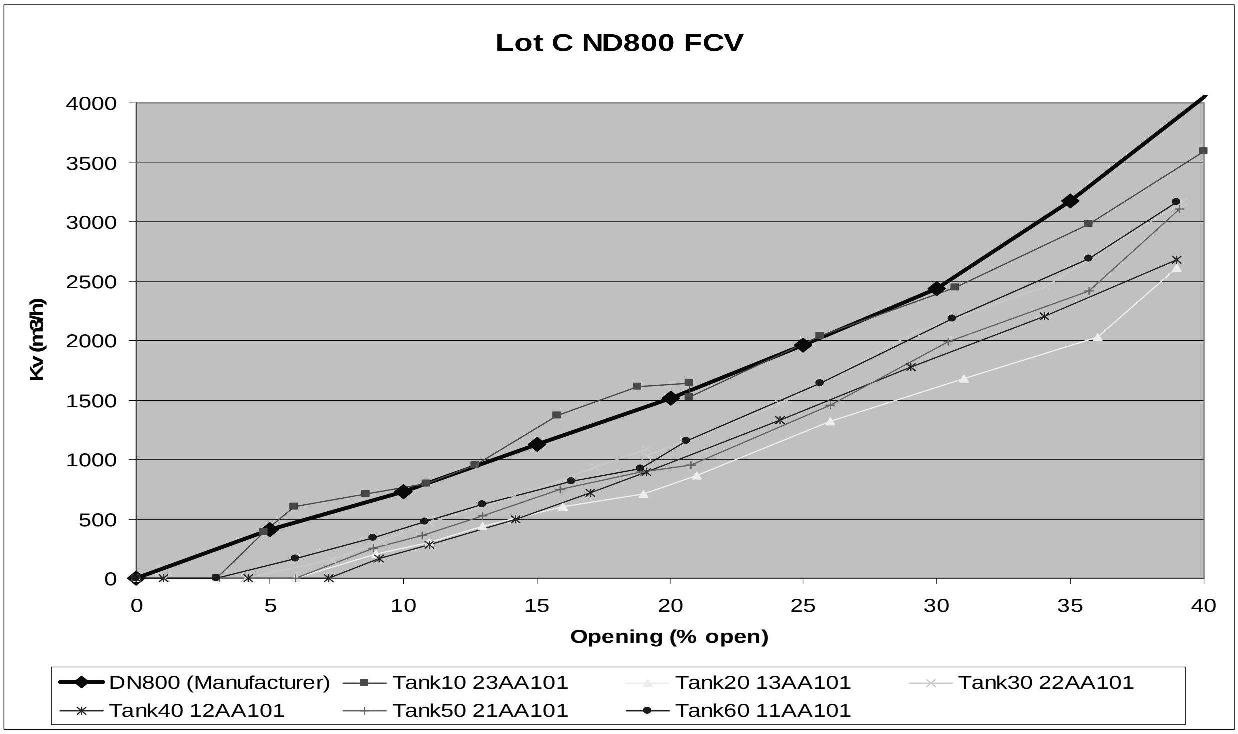

Figure 4 Kv characteristics of the control valve at Mirfa tank inlets as per site measurements

The figure above shows the results of the field measurement of the control valve Kv Characteristics. The initial Kv Characteristic, as provided by the manufacturer, is shown for comparison. It is clear from the figure above that at the freeze position of 5% opening, the actual Kv of the control valve is much smaller than the Kv provided by the manufacturer. In order to maintain the pressure within the acceptance criteria, the control valves were to allow 400 m^3/h at the freeze position. In reality, they allowed close to 0 m^3/h. De facto, the valves had closed in one single uninterrupted travel, causing over pressure in the pipeline. A number of possible causes have been investigated to explain this difference and submitted to the manufacturer. The following possible causes were submitted:

	Hypothesis	Status
1.	Approach flow to the valve affecting the Kv	Rejected because on Lot C, the worst Kv was recorded for a valve installed on a 50xdiameter straight tube
2.	Wrong Kv curve initially supplied by the manufacturer	The data was supplied three times during the project and were stamped and certified as tested by a laboratory
3.	Cavitation during closure of the valves	Staffs were located near the control valve to record cavitation noise during closure. No cavitation took place.

It was decided to adapt the closure pattern of the control valve to match the recorded Kv Characteristics and the freeze position was shifted from 5% to 12% in order to achieve the same flow rate through the control valve during the freeze period. The hydraulic model was updated with the measured Kv and the trial test was repeated showing close match with the model predictions.

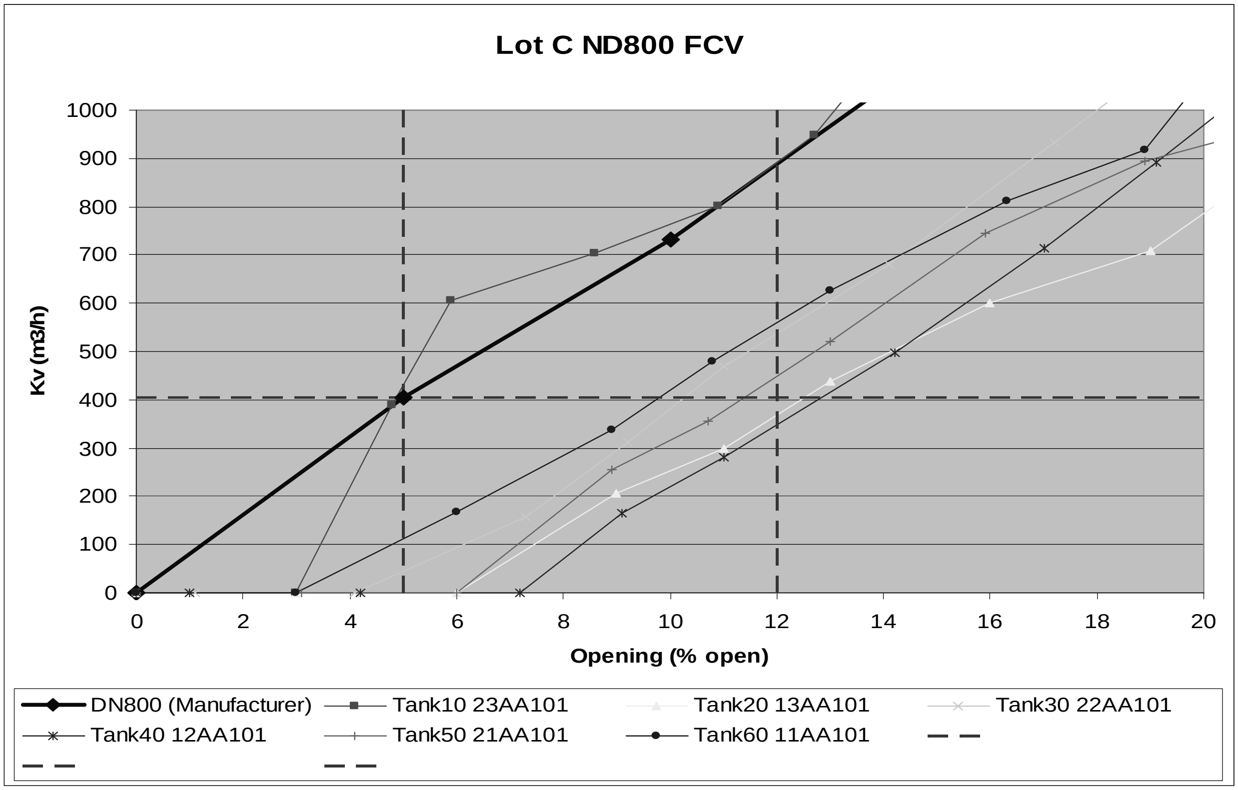

Figure 5 Adjustment of the closure pattern based on the measured Kv and position relation

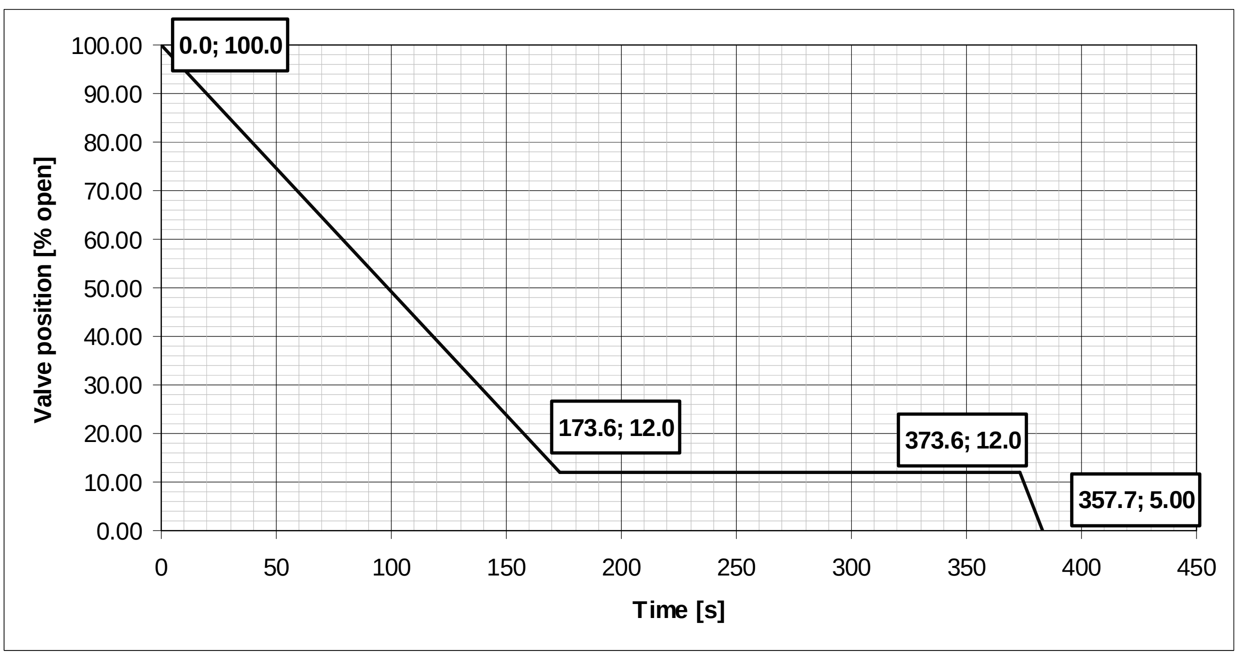

Figure 6 Closure pattern (Based on Site measurement of Kv) of Lot C tank inlet valves

Trial test performed with the updated control valve data

Emergency Shut Down at 60 MIGD (Test T3)

In this test, all opened control valve are closed simultaneously with a total flow rate of 60 MIGD in the pipeline. The pumps remain in auto mode and trip based on local flow and pressure deviations.

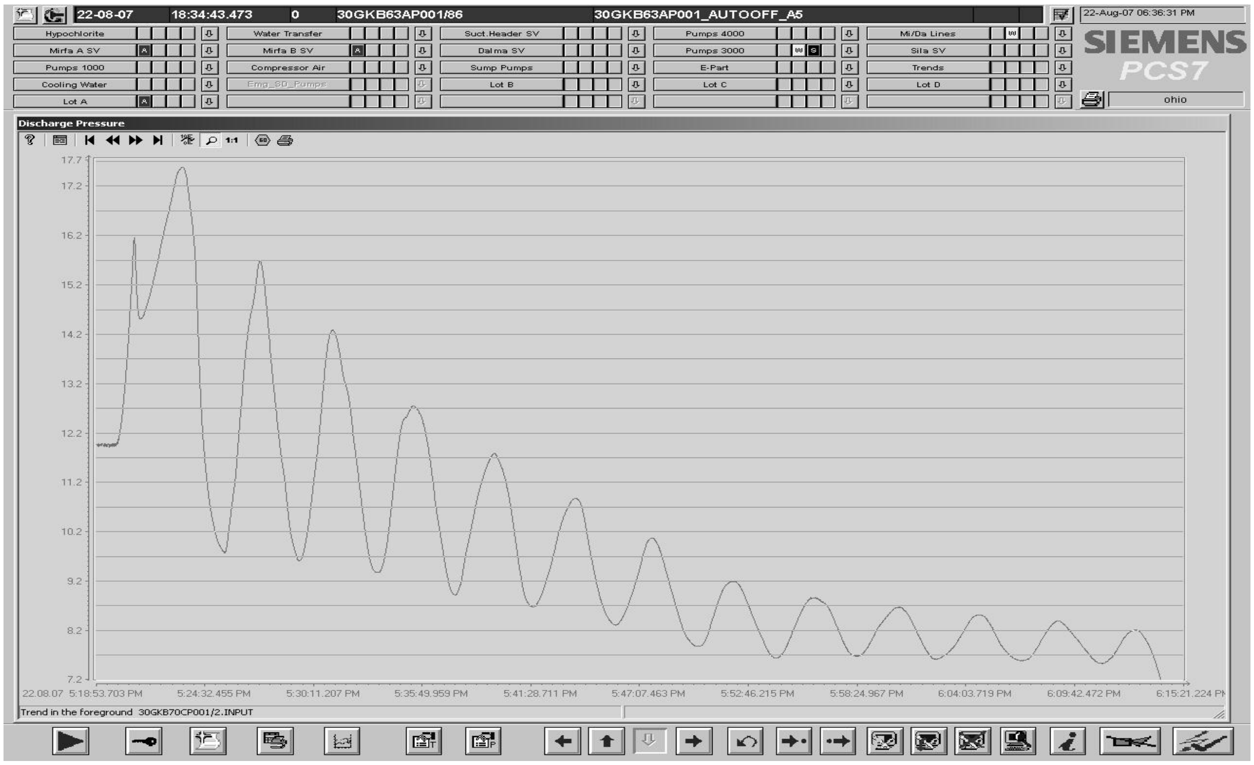

Figure 7 Recorded pressure at the pump station

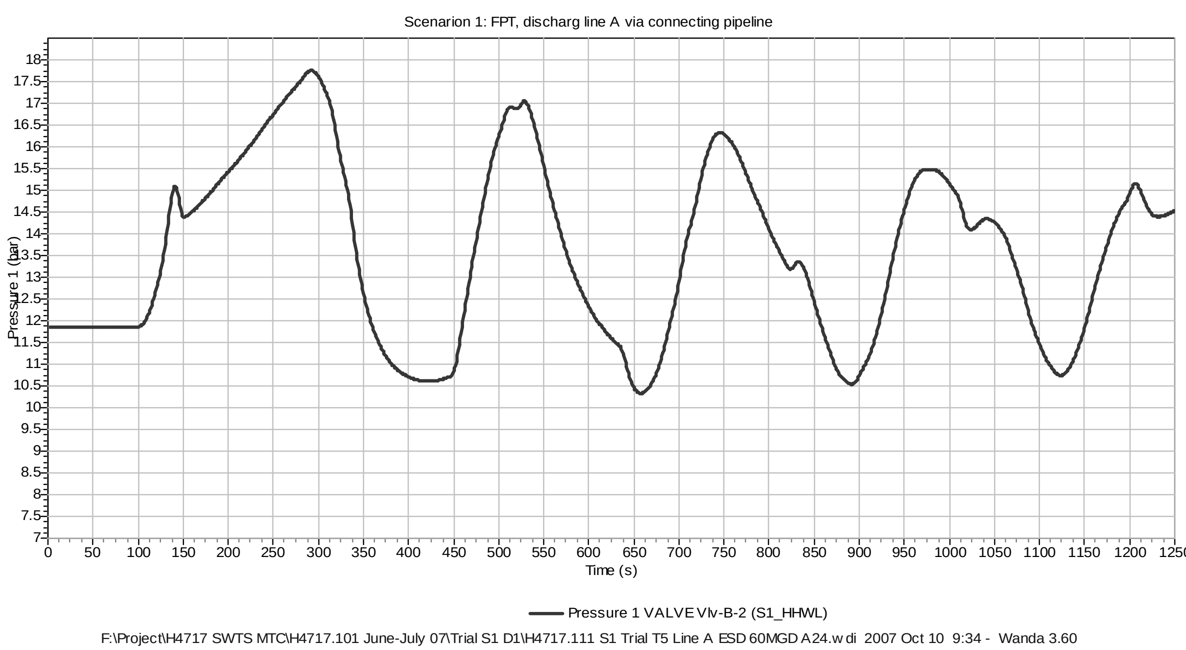

Figure 8 Predicted pressure at the pump station

The comparison between the maximum recorded pressure (17.5 barg) and the predicted pressure (17.8 barg) show a very close match (0.3 barg difference). This result validates not only the surge model but also validates the in-situ measurement of the control valve Kv and also provides convincing evidence that no cavitation occurs. The measurement of the Kv was performed at low upstream pressure and quasi-constant downstream pressure (due to the reservoir proximity). However, the closure of the control valve causes very high pressure upstream of the control valve. If there was cavitation at the valve and if this cavitation was causing a reduction of the Kv, it is doubtful that the model with the updated Kv would have predicted the correct pressures. Furthermore, during all tests, the control valves were manned by experienced staff who recorded the noise. There was no indication of cavitation.

The wave period as recorded in the DCS is 15:39 minutes (4L/T). This means a wave speed of 1032 m/s, based on a pipe length of 97 km. The surge software calculated a wave speed of 1036 m/s adjusted to 1031 m/s due to the time step limitation of the method of characteristics. This is a very close match. The following table gives the recorded and predicted value for the pressure which shows that the accuracy of the prediction is outstanding on the first peak but then quickly decreases as time passes.

Table 3 Summary table of recorded and predicted pressures

Period (pipe periods)	Recorded pressure	Predicted Pressure	Difference
1	17.5 barg	17.8 barg	0.3 barg
2	9.8 barg	10.6 barg	0.8 barg
3	15.7 barg	17.2 barg	1.8 barg
4	9.6 barg	10.3 barg	0.6 barg

Full Pump trip at 60 MIGD (Test T5)

In this scenario, all pumps are tripped at the total flow of 60 MIGD. The control valves remain in automatic mode and thus close in order to maintain the upstream pressure constant.

The minimum recorded pressure is 1.30 barg while the minimum predicted pressure is 1.0 barg. The predicted results are close to reality (0.30 barg difference). The model predictions are on the conservative side as the model is predicting lower pressures than reality. Furthermore, the general shapes of the recorded and predicted pressure time series are closely matched.

One should note that the accuracy of the full pump trip is notably worse than in the case of the emergency shut down case reported above. The main difference between these two cases is the influence and role played by the air vessels in the simulation. In the case of an ESD, the air vessel play very little role, indeed a simulation could be run without air vessels and still show closely match results (on the first wave period). However in the case of a full pump trip, the air vessel is the main driver of pressure in flow once the pumps have tripped. Unfortunately, the results for the air vessels in case T6 are not accessible. They were however recorded for the final case here below.

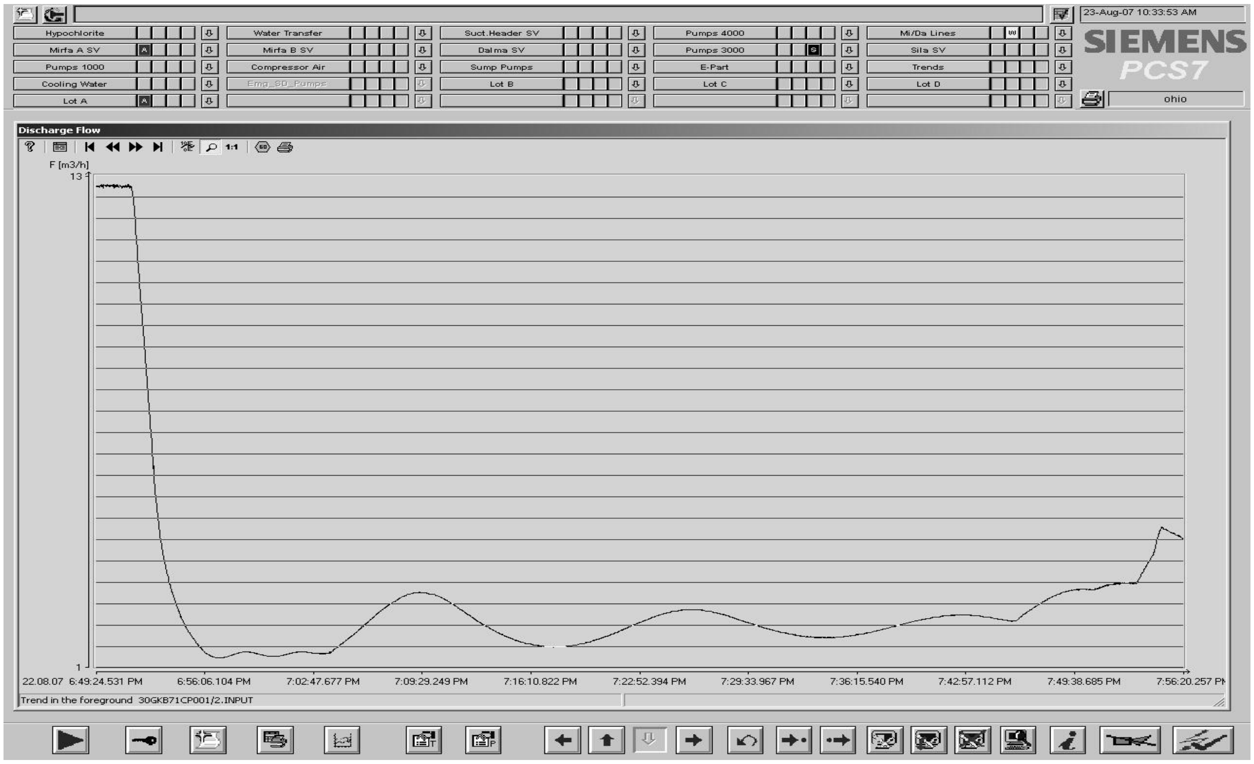

Figure 9 Recorded pressure at the pump station (vertical axis unit should read barg instead of m3/h)

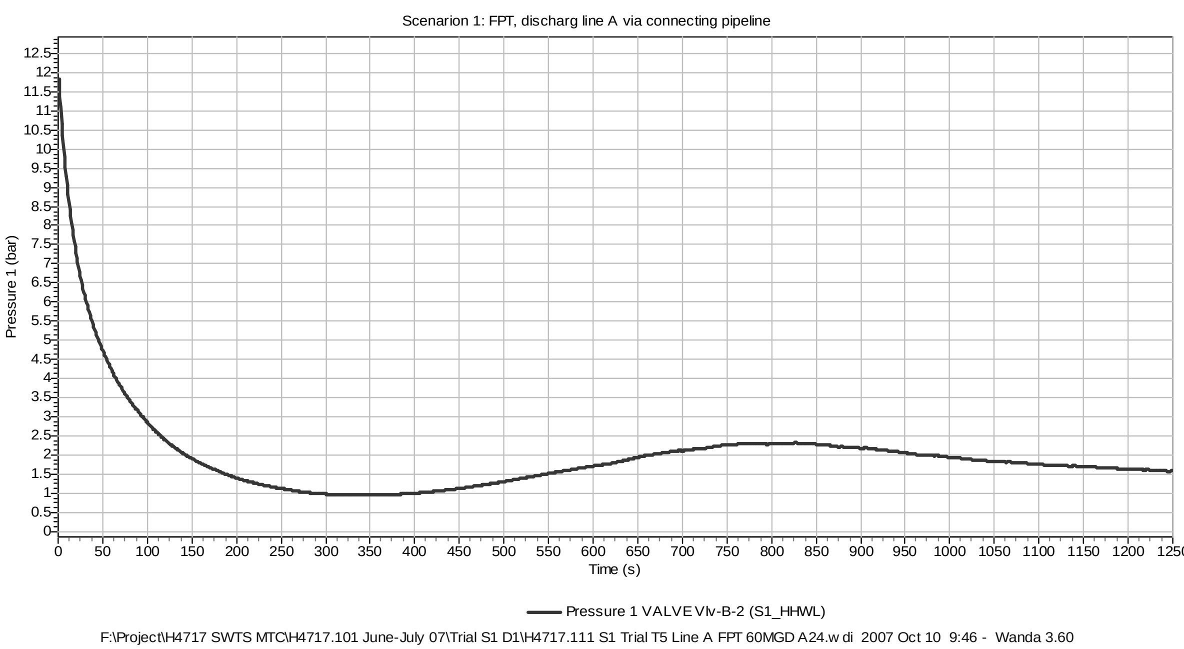

Figure 10 Predicted pressure at the pump station

Full Pump trip at 75 MIGD (Test T6)

This case investigated the full pump trip of the pumps at 75 MIGD. This case is not the design case for the system (maximum design flow is 60 MIGD). At the client's request, the air vessels of both lines (distribution and transmission) were pooled and a single pipeline operated at the flow of 75 MIGD.

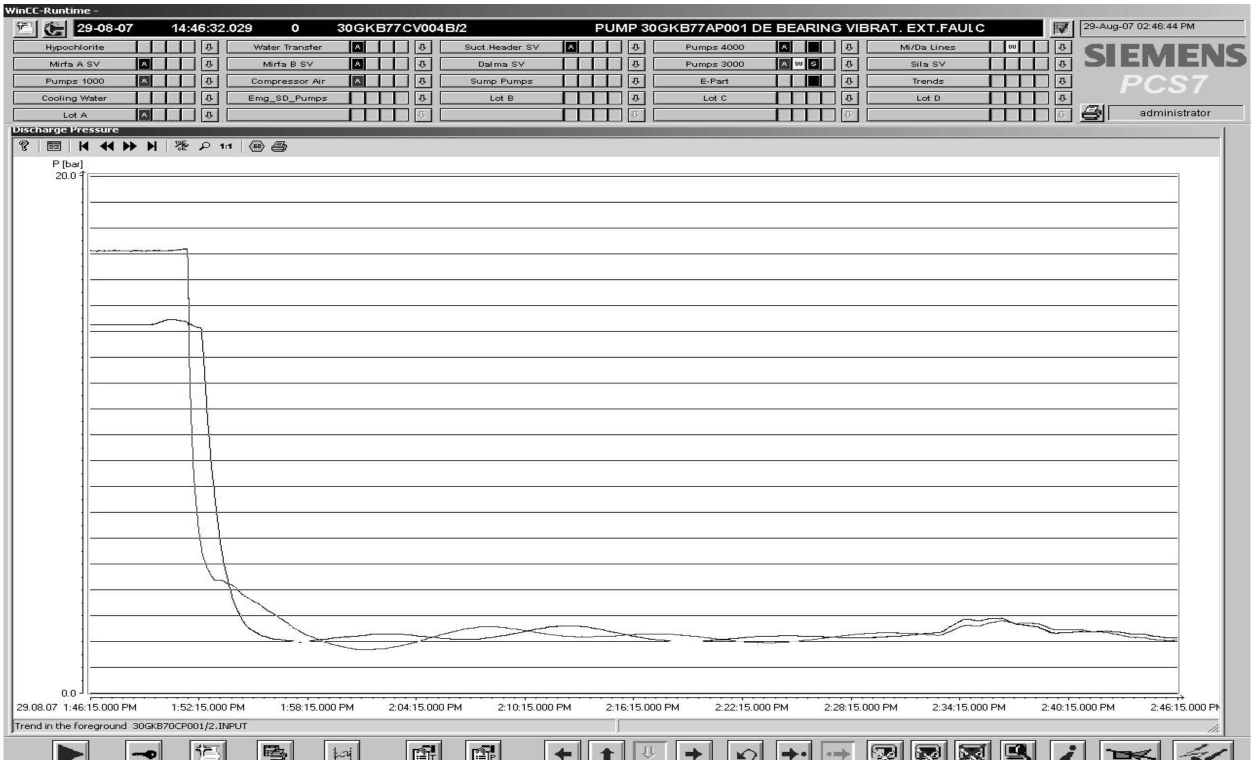

Figure 11 Recorded pressure at the pump station

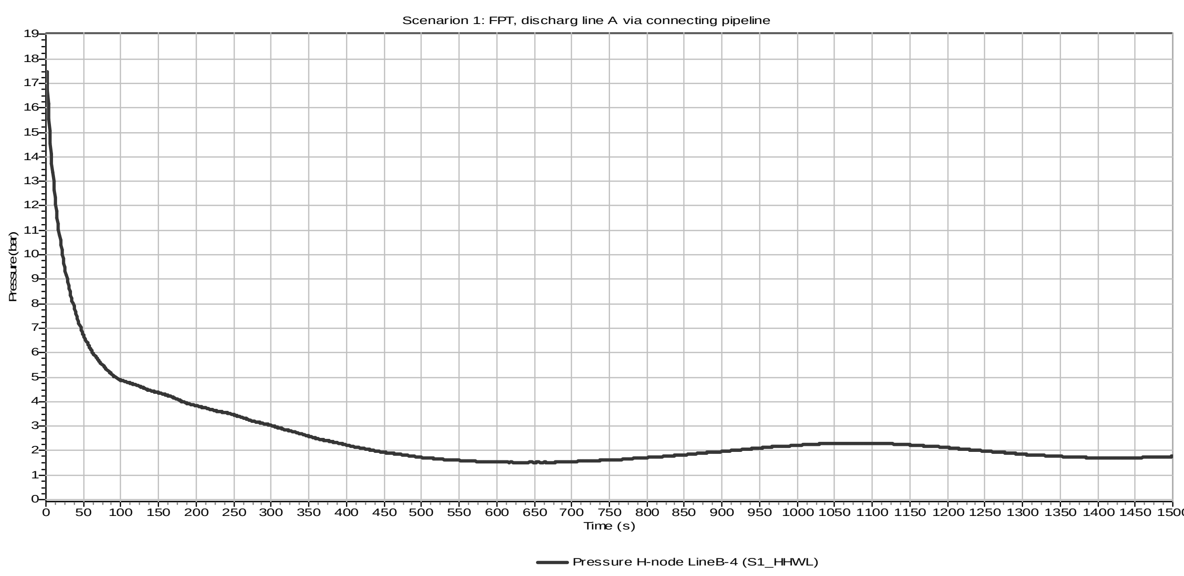

Figure 12 Predicted pressure at the pump station

The minimum recorded pressure is 1.64 barg which is very close to the predicted minimum pressure of 1.5 barg (difference of 0.1 barg which is even better than in the 60 MIGD case). Further in time, the predicted pressures are consistently lower than the recorded pressure which shows that the model is providing conservative results.

Air vessel levels have been recorded for this test and are presented below. The recorded fluid level drop in the vessels is 7.0 m while the predicted maximum drop is 9.3 m.

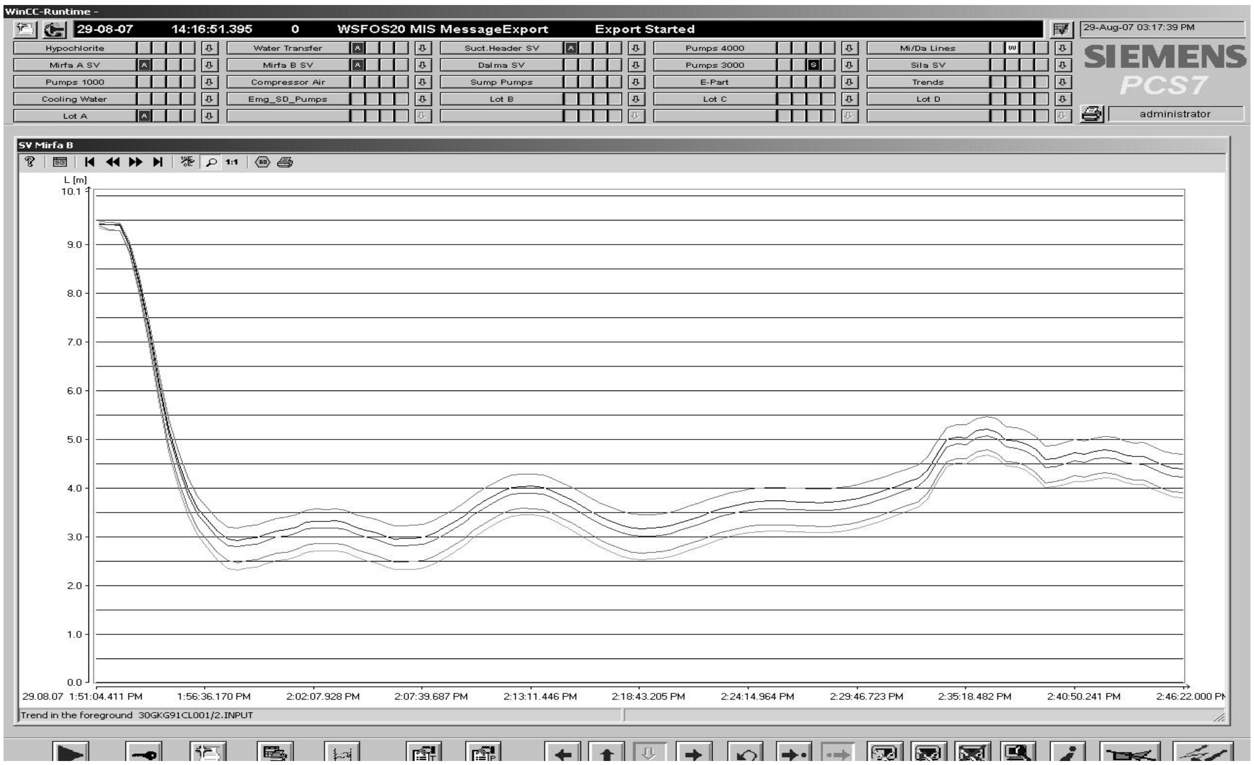

Figure 13 Recorded air vessel level (Polytropic index unknown)

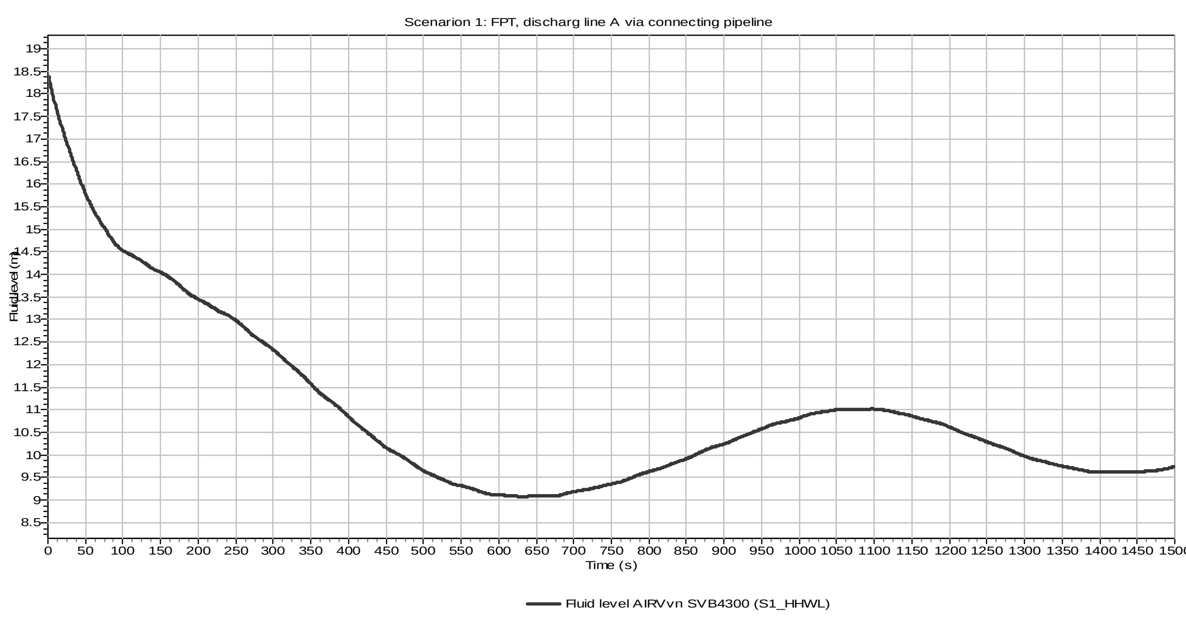

Figure 14 Predicted air vessel level (Polytropic index of 1.2)

There is a significant difference between the predicted and recorded value which is attributed to the Polytropic index. The design was performed using the full range of the Polytropic index (1.0 and 1.4 [-]) since this coefficient cannot be determined in advance. During the commissioning test, an average value of 1.2 [-] was chosen which clearly leads to inaccuracies of the model not only in predicted minimum fluid level but also in the minimum simulated pressures.

The interesting fact is however that the model predicts lower pressure than reality, which could be caused by the air vessels being more effective in reality. One can conclude in this case that the Polytropic index used for trial simulations is too large and a Polytropic index between 1.0 and 1.2 [-] would be more appropriate to model the minimum pressures in the pipeline. On the other hand, the model is predicting too low air vessels fluid level which leads exactly to the opposite conclusion that the Polytropic index is too small and the heat transfer during air expansion is not as efficient as anticipated. The Polytropic index in this case should be large than modelled, between 1.2 and 1.4 [-]. This is a dilemma that clearly calls for further investigation and study work.

Conclusions

The importance of accurate data to the accuracy of the results is well understood by the modeller but rarely is this also the case with the manufacturer or even the contractors. There is among modellers the common saying that the output will depend directly on the input. The surge modeller however is rarely in a position to ask for independent verification of the data but is yet expected to design multimillion equipments and to optimize these equipments to reach the lowest possible costs. There is here a inherent risk of failure. Some critical data should be certified by independent laboratories or at least field tested through a careful commissioning test. The benefit of these two activities far outweigh the costs to the project resulting from overdesigning or even pipeline failures.

The second conclusion is that modelling and in particular the WANDA software, once provided with accurate data can return accurate results in which complex protection systems, involving large air vessels, multistage valve operation and sophisticated control systems can be designed.

The final conclusion is that air vessel modelling is the weakest link in the model presented above. The lack of knowledge concerning the air expansion inside the vessel and thus the mathematical expression of the Polytropic index (constant parameter or heat transfer equation) is still the cause of inaccuracies. In the authors' opinion and in the case of this large pipeline system, the current approach has lead to the overdesigning of the vessels. There is a great incentive for further development and research on the heat transfer within the vessels during a surge event. TRANSCO and Deltares anticipate to conduct further work on this topic in the years to come.

Literature

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